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NGST Science Instrument Recommendations

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Summary of Recommendations

The following three-instrument complement provides a minimum for the NGST:

- **A camera with near IR and visible filters, sensitive over 0.6 - 5 μm**
- **A multi-object dispersive spectrograph (MOS) for 1 – 5 μm, with R~1000**
- **A combined camera/slit spectrograph for 5 – 28 μm with R~1500**

At least one of following key capabilities is also highly recommended:

- **An integral field spectrograph (IFS) for 1 – 5 μm**
- **A high-resolution camera, optimized for 0.6-1 μm**
- **An integral field spectrograph (IFS) for 5 – 28 μm**

Outline

1. Introduction

The first concept for the Next Generation Space Telescope (NGST) instrument complement was developed for the Yardstick mission study in 1996 by the NASA - STScI team. It was spelled out in the 1997 NGST project report "Visiting a Time when Galaxies were Young," http://oposite.stsci.edu/ngst/initial-study/, edited by H. S. Stockman. It comprised four instruments: a near IR camera, a near IR multiobject spectrograph based on the micromirror array being developed for projection television by Texas Instruments, a mid IR camera, and a mid IR spectrograph. For this study, near IR(NIR) was defined as 1 - 5 μm, and mid IR (MIR) as 5 - 30 μm. The possibility of a coronagraph was discussed, but it was not included in the Yardstick mission study.

These instrument concepts were developed to respond to the scientific objectives described in the 1996 report "HST and Beyond," prepared by an AURA committee chaired by Alan Dressler, http://ngst.gsfc.nasa.gov/project/bin/HST_Beyond.PDF. This report outlined several top priority objectives in extragalactic astronomy, including seeing the first luminous objects to form after the big bang, understanding the structure of the universe through analysis of the distance scale using supernovae, and learning about the clustering of matter. Infrared capabilities are essential because the expansion of the universe redshifts the primary starlight from the UV into the near IR. Wavelengths grow as $(1+z) = R_{now}/R_{then}$, where z is the redshift and R_{now} and R_{then} are the radius of the universe now and at the time that a photon was emitted. The report also included objectives in the areas of star and planet formation and evolution, which can be studied with infrared light because it penetrates the obscuring dust clouds where the early history of stars and planets occurs.

2. The NGST is unique in different ways at each available wavelength.

- 0.5 - 1 μm wide-band photometry and wide field high quality imaging. On the ground, adaptive optics is not yet fully effective, but ground-based spectroscopy is very competitive. Telescopes much larger than the 10-m Keck are being discussed and would be perfect complements to the NGST, just as the Keck complements the Hubble Space Telescope. It is important to see the Lyman break, which falls in this wavelength range for fairly high redshifts. This wavelength range offers the best angular resolution for a given aperture, but the NGST mirror may not be diffraction limited for $\lambda < 2$ μm.
- 1 - 2 μm imaging and multiobject spectroscopy at moderate resolution. Adaptive optics is very effective on the ground, and may become even better with advanced multi-laser, multi-guide-star, multi-conjugate versions. Numerous atmospheric spectral lines limit sensitivity for low spectral resolution, and airglow is brighter than the zodiacal light even between the lines.
- 2 - 5 μm imaging and multiobject spectroscopy. In this band, thermal emission on the ground is severe. NGST will observe highly redshifted, star-forming galaxies and moderately redshifted ($z < 3$) older, cooler galaxies.
- 5 - 28 μm imaging and spectroscopy, with sensitivity limited by the Zodiacal light out to 10 μm and the cutoff of Si:As detectors at 28 μm Thermal emission on the ground is severe, and there is a premium on aperture for angular resolution. The SIRTF (Space Infrared Telescope Facility) will observe in this region but has only 85 cm aperture. The NGST will see interstellar material (near and far), solid bodies, and obscured star formation.

- High contrast observations at all wavelengths. NGST will be unique in its potential for discoveries of planetary systems, and protoplanetary dust disks. It may also show galactic nuclei and black holes better than ever before.

3. The four Project Scientists and their deputies work with the Ad Hoc Science Working Group (ASWG) to provide scientific leadership of the NGST project.

John Mather is the NASA Project Scientist, with deputies Matthew Greenhouse, Eric Smith, and Richard Burg. Peter Stockman, Simon Lilly, and Peter Jakobsen are the STScI, CSA, and ESA Project Scientists. The ASWG was originally populated by the winners of a NASA competitive selection, and augmented by special appointments for particular research areas, and by representatives nominated by ESA and CSA. The main task for the ASWG is the creation and prioritization of representative science programs and capabilities for the NGST, and the analysis of potential instrument complements. The ASWG members are tabulated in Table 1 below, and at http://ngst.gsfc.nasa.gov/project/Groups/SciWG/.

Santiago Arribas, I. Astro. Canarias	John Mather, GSFC (Co-Chair)
Jill Bechtold, Steward Observatory	John MacKenty, STScI
Mike Fall, STScI	Mark McCaughrean, Astr. I. Potsdam
Robert Fosbury, ESO/STECF	Michael Meyer , Steward Observatory
Jon Gardner, GSFC	Harvey Moseley, GSFC
James Graham, UC Berkeley	Phil Nicholson, Cornell Univ.
Tom Greene, NASA Ames	Takashi Onaka, U. Tokyo
Matt Greenhouse, GSFC	Marcia Rieke, Steward Observatory
Don Hall, Univ. Hawaii	Mike Rich, UCLA
John Hutchings, DAO	Peter Schneider, Max Planck Inst.
Avi Loeb, Harvard	Gene Serabyn, JPL
Peter Jakobsen, ESTEC	Massimo Stiavelli, STScI
Bob Kirshner, Harvard	Peter Stockman, STScI (Co-Chair)
Simon Lilly, Univ. Toronto	John Trauger, JPL
Bruce Margon, Univ. Washington	Ewine van Dishoeck, Leiden

Table 1. ASWG Membership

4. Design Reference Mission

The scientific implications of Dressler et al. report were developed into a Design Reference Mission. The first DRM was reported by Stiavelli et al. at the STScI, (1997, http://ecf.hq.eso.org/newsletter/stecf-nl-24/) and was a list of proposed observing programs with desired fields of view, sensitivities, and numbers of objects to be measured. The DRM provides the basis of a numerical metric for the performance of the instruments and spacecraft, and the observations outlined could become key observational projects when the NGST scientific programs are finally chosen by competition. DRM Version 2.1 represents the current best parameterization and prioritization following the June 1999 ASWG meeting. In this version the yardstick mission can complete the DRM in 2.5 years. The ASWG added two new themes to the original: Nearby

Planet detection, and Astrochemistry/Astrobiology. Neither requires a completely new instrument capability.

The DRM programs fall into five major themes, listed with the estimated fraction of the observing time:

- Cosmology and the Structure of the Universe (21%)
- The Origin and Evolution of Galaxies (33%)
- The History of the Milky Way and its Neighbors (15%)
- The Birth and Formation of Stars (16%)
- The Origins and Evolution of Planetary Systems (15%)

The Design Reference Mission is described at http://www.ngst.nasa.gov/science/drm.html, and specific programs are at http://www.ngst.stsci.edu/drm/programs.html. The Project recognizes the need to balance stability of requirements with scientific accuracy and relevancy. The prime DRM documents (NGST-SCI-SPEC-0004 [Excel], 0013 [ASCII]) are now under configuration control. Major version changes (e.g., version 2 to 3) will only be made when authorized by the ASWG.

The contents have been discussed extensively by the ASWG, and ranked in order of priority. The ASWG considers the top seven DRM elements to be the defining core mission. The ranking confirmed the original approach of the Yardstick mission, in which the near IR instruments are both essential and the mid IR instruments are very important. The mid IR includes specific DRM goals and provides a very large “discovery space,” in the sense that the NGST capabilities so far exceed all prior missions that important new types of objects and phenomena might well be found. The ASWG also showed that extension of the wavelength range down to 0.6 μm is critically important to cosmology, since the 0.1216 μm Lyman α line (the longest wavelength at which the intergalactic hydrogen becomes opaque) remains at wavelengths below 1 μm for redshifts out to z=7.2, and the Lyman break does not reach 1 μm until z= 10. This line and the Lyman continuum break are the strongest markers for high redshift sources. Although the visible wavelengths can be observed from the ground, the ASWG believes that the NGST will still have important advantages for faint objects because of its lower natural background and sharper point spread function, which reduces the confusion of overlapping sources. Extensions to mid IR wavelengths were also found very important both for the study of high redshift galaxies and for penetrating dust to understand the physics of star and planet formation. The NGST background between 5-10 μm is relatively low and permits the spectroscopic detection of the 2.3 μm CO bandhead and the diagnostic, emission lines from hydrogen, oxygen, and nitrogen to redshifts as high as $z \sim 5$-15 and PAH emission in dust enshrouded starforming galaxies to $z < 5$.

5. Instrument Plans

NASA's Goddard Space Flight Center (GSFC) is managing the NGST mission, and will be responsible for the Integrated Science Instrument Module (ISIM). GSFC will provide the supporting structure, thermal environment, and electrical interface to the cold optics and detectors of the various instruments, along with the data system and the flight software and ground support equipment (GSE). International contributions of instrumentation will be received by GSFC. GSFC will integrate and test the modules and provide a complete integrated package as Government

Furnished Equipment (GFE) to the observatory prime contractor.   GSFC will lead an Integrated Product Team (IPT) for the development of the ISIM, and its members will include the STScI, ESA, CSA, the prime contractor, and the flight instrument principal investigators when they are chosen. Ongoing instrument progress can be monitored via the web site http://www701.gsfc.nasa.gov/isim/isim.htm.

The Phase A observatory study contractor teams (Lockheed Martin and TRW/Ball Aerospace) have been asked to study mission concepts that would provide sensitivity limited by the zodiacal light for $\lambda < 10$ µm. This plan is the result of an engineering trade study, which showed that a 30 K instrument chamber can be readily achieved with radiative cooling, and that the observatory designs that allow this temperature are naturally capable of reaching the zodiacal limit at 10 µm (Bély et al., 1999; http://www.ngst.nasa.gov/cgi-bin/doc?Id=226).

The NASA, ESA, and CSA management will consider the recommendations of the ASWG and develop an allocation of international responsibilities around April 2000. ESA will solicit its instrument contribution from industry, with a separate scientific team. NASA will solicit complete investigations, including both scientific programs and instruments, in 2001, with a selection planned for 2002. The CSA budget is not sufficient for an entire instrument so a partnership with NASA or ESA is expected.

NASA plans to issue a NASA Research Announcement (NRA) in January 2000, to cover instrument technology development. Examples of topics to be covered include: instrument technologies for multi-object and integral field spectroscopy, conventional and micro-electro-mechanical systems (MEMS) cryogenic infrared tunable filters, laboratory and ground-based demonstrations of NGST science instrument concepts, laboratory demonstration of long life flight cooling systems for 6 K IR focal plane arrays, and techniques for characterization and operation of detectors under ultra-low background conditions, modeling and simulations relevant to enhanced understanding of NGST instrument requirements

6. Instrument Possibilities and Studies

The generic possibilities for instruments include:

- Cameras with filters and tunable filters
- Dispersive spectrographs using prisms, gratings, grisms, or echelles
- Fourier spectrographs (cameras with adjustable cosine filters)
- Multiobject spectrographs, using micromirrors, microshutters, multiple discrete slits, or movable fibers on actuators
- Integral field spectrographs, using image slicers, fibers, or microlens arrays
- Coronagraphs, using graded Lyot stops, dark spots, phase masks, and high order deformable mirrors
- Combinations of all sorts (filters and gratings, filters and Fourier, Fourier and dispersive, beam switches for shared detectors, etc.)

NASA carried out a Baseline ISIM Design Study from 1996 to 1999. The goals of this study were to demonstrate mission science feasibility, assess ISIM engineering and cost feasibility, identify ISIM technology challenge areas, and enable smart customer procurement of NGST instruments. The yardstick architecture was constrained to be consistent with the yardstick mission concept, an 8-m telescope with a particular design. In this plan, the ISIM must provide accommodation for wavefront sensors, fine guidance sensors, and fast steering mirrors.

The ISIM design has evolved considerably since its 1996 first edition. In that study there was a single highly integrated instrument module that performed all the necessary functions. It was felt that this was the only way to meet the cost and mass goals, and indeed beryllium structures were used to help with the mass. By 1999, the design had become modular, with many segments that can be installed as units. This modularity is important for simple assembly, test, and integration, as well as to enable the contributions of multiple organizations to a single whole. The new design also uses an aluminum structure to reduce cost, and it is hoped that the new launch vehicles will have sufficient capabilities to allow this. The ISIM was designed with sufficient detail to support accurate cost and mass estimates.

In 1998, NASA, ESA, and CSA held competitions for instrument studies. The reports from all the specific studies are at http://www.ngst.nasa.gov/science/isimpage.html. The NASA-funded instrument studies include:

- J. Bechtold, T. Greene: U. of Arizona & Lockheed Martin Corp.: 0.3 - 40 µm imaging, spectroscopy, and ISIM layout
- J. Graham: U. of California & ITT Industries & Lawrence Livermore Labs, 1 - 15 µm Fourier transform imaging spectroscopy
- J. MacKenty: STScI/ Ball Aerospace/ GSFC, 1 - 5 µm multi-object spectroscopy with MEMS micro-mirrors
- H. Moseley: GSFC, MEMS micro-shutter aperture control for multi-object spectroscopy
- G. Serabyn: JPL, 5 - 28 µm camera/spectrometer and Sorption cryocooler
- J. Trauger: JPL, 1-5 µm high contrast coronagraph with deformable mirror

In addition, the University of Colorado submitted a study report, showing how an integrated instrument package could share detectors among many instrument capabilities and configurations.

The CSA NGST Science Instrument Studies include:

- Near-IR MOS/IFS: David Crampton (HIA/DAO) & CAL (Ottawa)
- Visible Imager: Paul Hickson (UBC) & CAL (Ottawa)
- IFIRS Imaging FTS: Simon Morris (HIA/DAO) & Bomem(Quebec) (collaboration with US Graham/ITT study)

European instrument concept studies include:

- Near-IR Wide Field Camera: O. Lefévre (LAS) & Dornier Satellitensysteme (DSS)
- Near-IR Imaging Fourier Transform Spectrograph: O. Lefévre (LAS) & DSS
- Near-IR Integral Field Multi Object Spectrograph: O. Lefévre (LAS) & DSS
- Mid-IR Camera: G. Wright (ROE) & DSS
- Mid-IR Integral Field Spectrograph: G. Wright (ROE) & DSS
- Visible Wide Field Camera: M. Ward (Leicester) & Matra Marconi Space (MMS)
- Visible High Resolution Camera: M. Ward (Leicester) & MMS
- Visible Integral Field Spectrograph: M. Ward (Leicester) & MMS
- Coronography: F. Vakili (OCA)

7.0 Instrument Concept Review Process

In the summer of 1999, prior to the receipt of the instrument study reports, the NGST project chartered John Huchra to chair a committee and develop a generic comparison of near IR spectrographs. This report may be found at http://www.ngst.stsci.edu/nir_spec_study99/nir_summary.html. It advocated both high resolution and wide-field modes, specified the desired spatial and spectral resolution, and recognized the potential benefits of the Multiobject Spectrometers (MOS).

A Technical Review Panel of 29 members from NASA, ESA, CSA, industry, and universities evaluated the technical readiness of the concepts reported by the many study teams. The panel also made cost estimates on a uniform basis, using a parametric cost model developed by the Resource Analysis Office (RAO) of the Goddard Space Flight Center. The cost estimates were compared with the estimates prepared by the instrument study teams, and the agreement was reasonable considering that the parametric estimates themselves allow ranges of factors of 2 or 3 from optimistic to pessimistic. NASA experience suggests that parametric estimates are on average as reliable as the estimates prepared by proposers. The report of the technical panel, chaired by P. Geithner of NASA/GSFC, is available at http://www.ngst.nasa.gov/cgi-bin/doc?Id=569.

A detector technology report was also prepared by a team led by C. McCreight of NASA/Ames, and is available at http://www.ngst.nasa.gov/cgi-bin/doc?Id=539. Some important conclusions of the report are that although good sensitivity is already available, significant technology development is required to ensure that the large format detectors needed by NGST will be available when needed. Also, it appears that both InSb and HgCdTe detectors can have very good quantum efficiency at visible wavelengths, down to 0.6 µm. Hence, it is possible to design a visible/near IR camera that uses a single detector type. The report also shows that although there are several possible dopants for Si:X detectors in the mid IR, the only one that seems likely to be ready in time is Si:As. Most of the spectroscopic observations planned by the ASWG will require the best possible sensitivity, but most of the wide-band imaging will be limited by the quantum fluctuations of the infrared photons even with today’s detectors. Because of the importance of the spectroscopy, investment in improved detector sensitivity has a very high payoff for the scientific performance of the NGST. This will require significant investment in detector characterization at low background levels, especially in the near IR.

The ASWG reviewed the scientific capabilities of the instrument concepts in the light of the NGST Design Reference Mission. The ASWG core group included 14 US, 6 European, 2 Canadian, and one Japanese member, who met with the leaders of the instrument concept studies, including 7 US, 3 European, and 3 Canadian scientists – the combined group representing 26 international institutions. The ASWG core group was constituted to avoid or manage the conflicts of interest of participants in the instrument concept studies.

Three subcommittees were appointed from the ASWG. The near IR camera subcommittee was chaired by M. Stiavelli, the near IR spectrograph subcommittee by M. Rieke, and the mid IR subcommittee by M. Meyer. The spectrograph subcommittee did not agree exactly with the Huchra committee report. In particular, the Huchra committee did not advocate spectroscopy at moderate resolution (R~100), while the Rieke subcommittee argued strongly for it and urged that it be provided in either the camera or the spectrograph. The report of the ASWG process, including the subcommittee reports and the final recommendations, was prepared by H.S. Stockman and is available at the NASA web site as document #567. Although the reports were very thorough, not all the recommendations were accepted by the larger group.

8. Recommendations

On the basis of this process, **the ASWG core group has recommended an instrument complement for the NGST.**

Relative to current or planned observatories, the NGST has unique advantages in image quality, field of view, low background light, and environmental stability. These apply at low spectral resolution from 0.6 to 2.5 μm, and for all spectral resolutions from 2.5 to 28 μm. NGST will have diffraction-limited imaging at 2 μm and photon background dominated by the zodiacal light at $\lambda <$ 10 μm. The ASWG ranks the priorities for NGST instrumentation as: 1) ultimate sensitivity, 2) coverage of the full 0.6 μm – 28 μm wavelength range, 3) exploitation of NGST's spatial resolution, and 4) maximizing the multiplexing gain in terms of the number of objects that can be observed simultaneously.

The ASWG believes that there is no acceptable two-instrument complement for the NGST.

The following three-instrument complement provides a minimum for the NGST mission but results in the loss of several key scientific capabilities in the core NGST science area. The ASWG thus identified three additional instruments, smaller and cheaper than the initial three, which would restore some of these lost core-science capabilities and recommends that one of these should be included as a fourth instrument.

The core three-instrument complement consists of:

- **A camera with NIR and visible filters and sensitive over the 0.6 - 5 μm wavelength range**, with a 4′x4′ field of view, and 0.03" pixels ($\lambda/2D$ at 2.4 μm) requiring an $8k^2$ array detector. A basic spectroscopic capability with $R=\lambda/\delta\lambda=100$ is essential and should be provided either in this camera (e.g. with a slit and grism) or in the spectrograph described below. Sub-arrays within this camera could possibly serve as a guide star and wavefront sensor and a low-cost coronagraphic capability could also be provided. This camera is required for most of the NGST highest-ranked science programs, including the detection of first light from the first star-clusters or black-holes, the study of high redshift galaxies seen in the process of formation, dark matter (through studies of weak gravitational lensing), the discovery of high redshift supernovae, studies of the stellar populations in nearby galaxies, of young stellar objects n our own Galaxy, and of Kuiper Belt Objects (KBO's) in our own Solar System.

- **A multi-object dispersive spectrograph (MOS) for 1 – 5 μm, with R~1000**, with pixels matched to the sizes of high redshift galaxies (~0.1"), and covering a 3′x3′ field or larger, and capable of observing > 100 objects simultaneously. Ideally, the spectral resolution would be selectable and would extend down to R ~ 100, unless this capability was provided in the camera above. The preferred technology for this instrument is the MEMs (micro-electro-mechanical) selectable slit or mirror approach. In the event that this is unavailable, a MOS with mechanically positioned slits (either with jaws or optical fibers) or a wide-field integral field spectrograph (IFS) would be acceptable alternatives at reduced observing efficiency. A Dispersed Imaging Fourier Transform Spectrograph was also considered but seemed more complex and costly. The key scientific objectives of this instrument would include studies of star formation and chemical abundances of young galaxies at high redshifts, measurement of the hierarchical development of large scale structure at high redshifts, and the study of the initial mass function in young stellar clusters.
- **A combined camera/slit spectrograph for 5 – 28 μm with R=1500 and a 2′x2′ field** sharing a single focal plane array. A low-cost coronagraphic capability could be provided. The scientific objectives for this instrument include the study of old established stellar populations at high redshift, of obscured star formation and diagnostic emission line features at z ~2, Hα emission to z ~ 15, and AGN at z ~1, local group AGB stars, the cool stellar mass function, the physics of protostars, circumstellar disk mineralogy, the sizes of KBO's, and faint comets. This instrument will be ideal for the detailed follow-up study of new mid-infrared sources that will be discovered by SIRTF and ISO.

Some key scientific capabilities for NGST that are missing from the above instrument suite could be restored by including any one of the following as a small inexpensive fourth instrument. These have been ranked by the ASWG as being of equal scientific priority.

- **An integral field spectrograph (IFS) in the NIR waveband**, probably using an image slicer, and able to exploit the full spatial resolution of the NGST at spectral resolutions up to R ~ 5000 required to resolve the kinematics of small galaxies. This instrument would cover a contiguous field of 2"x2" with < 0.1" pixels. Key scientific objectives include measuring the masses of young galaxies at high redshift, the study of galactic nuclei at high resolution, and of dense stellar clusters.
- **A high-resolution camera, optimized for 0.6-1 μm and capable of sampling the full spatial resolution** of NGST at short wavelengths. This instrument is envisaged as having ~0.01" pixels (λ/2D at 1.2 μm) and covering a minimum 1′x1′ field. Key scientific objectives include studies of the morphology of high redshift galaxies, the study of stellar populations in nearby galaxies, the determination of the ages of globular clusters through observations of white dwarfs, and the study of circumstellar disks.
- **An -integral field spectrograph (IFS) in the MIR** waveband with R=3000-5000 with high spatial resolution (~0.3" FWHM) sampling of a contiguous (2"x2") region over 5 – 28 μm. These spectral resolutions are required for studying gas phase physics in circumstellar disks, comets, and early protostars. This instrument would replace the R=1500 capability of the combined MIR camera/spectrograph described above.

The most costly parts of the proposed instrument suite are the detectors and associated electronics, and the MEMS device for the multi-object spectrograph. These are the most important areas for technology development funds. The technologies for a MEMS multi-object slit or mirror device and, to a lesser degree, the approach of constructing discrete slits with actuators, are not mature and the ASWG recommends an aggressive development of these items. Vibration-free coolers for λ>5 μm detectors are also challenging and require further development. There are several choices, including solid hydrogen, sorption-pumped hydrogen, and a turbo-Brayton cooler like the one developed for NICMOS on HST.

9. Feedback to NGST

Comments should be sent to john.mather@gsfc.nasa.gov. We are interested in suggestions in all scientific and policy areas, to help ensure that this mission does the most exciting science within the constraints of schedule and budget.

10. Acknowledgments

The NGST project benefits strongly from the support of top NASA management, beginning with the statement made by Dan Goldin, the NASA Administrator, to the American Astronomical Society in 1996. He said the “HST and Beyond” report was much too cautious in requesting a 4-m NGST, and said NASA would build an 8-m NGST. The NGST also benefits greatly from the work of Alan Dressler, who took the “HST and Beyond” report to Dan Goldin and established a relationship of trust. The GSFC ISIM study received scientific leadership from Matt Greenhouse, who is also the main point of contact for the instrument studies funded by NASA. He is the originator of much of the process described above.

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